

Improved Measurement of  $CP$  Violation in Neutral  $B$  Decays to  $c\bar{c}s$ 

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We present updated measurements of time-dependent  $CP$  asymmetries in fully-reconstructed neutral  $B$  decays to several  $CP$  eigenstates containing a charmonium meson. The measurements use a data sample of  $(383 \pm 4) \times 10^6$   $\Upsilon(4S) \rightarrow B\bar{B}$  decays collected with the *BABAR* detector at the PEP-II  $B$  factory. We determine  $\sin 2\beta = 0.714 \pm 0.032$  (stat)  $\pm 0.018$  (syst) and  $|\lambda| = 0.952 \pm 0.022$  (stat)  $\pm 0.017$  (syst).

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The standard model (SM) of electroweak interactions describes  $CP$  violation as a consequence of an irreducible phase in the three-family Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. In the CKM framework, neutral  $B$  decays to  $CP$  eigenstates containing a charmonium and a  $K^{(*)0}$  meson through tree-diagram dominated processes provide a direct measurement of  $\sin 2\beta$  [2], where the angle  $\beta$  is defined in terms of the CKM matrix elements  $V_{ij}$  as  $\arg[-(V_{cd}V_{cb}^*)/(V_{td}V_{tb}^*)]$ .

We report updated measurements, based on a sample of  $(383 \pm 4) \times 10^6$   $\Upsilon(4S) \rightarrow B\bar{B}$  decays, of  $\sin 2\beta$  and of the parameter  $|\lambda|$ . Here  $\lambda = (q/p)(\bar{A}/A)$  [3],  $q$  and  $p$  are complex constants that relate the  $B$ -meson flavor eigenstates to the mass eigenstates, and  $\bar{A}/A$  is the ratio of amplitudes of the decay of a  $\bar{B}^0$  or  $B^0$  to the final state under study. We reconstruct  $B^0$  decays to the final states  $J/\psi K_S^0$ ,  $J/\psi K_L^0$ ,  $\psi(2S)K_S^0$ ,  $\chi_{c1}K_S^0$ ,  $\eta_c K_S^0$ , and  $J/\psi K^{*0}$  [4]. Since our previously published result [5], we have added  $157 \times 10^6$   $B\bar{B}$  decays and applied improved event reconstruction algorithms to the entire dataset. We have also developed a new  $\eta_c K_S^0$  event selection based on the Dalitz plot structure of the  $\eta_c \rightarrow K_S^0 K^+ \pi^-$  decay, and have performed a more detailed study of the  $CP$  properties of the background events, which results in reduced systematic errors. We now include the  $J/\psi K_L^0$  and  $J/\psi K^{*0}$  modes in the sample to measure  $|\lambda|$ , and we report individual measurements of  $\sin 2\beta$  and  $|\lambda|$  for each of the  $CP$  decay modes used in the analysis. Finally, we present separate results for the  $J/\psi K_S^0(\pi^+ \pi^- + \pi^0 \pi^0)$  [6], and  $J/\psi K^0(K_S^0 + K_L^0)$  modes.

We identify (tag) the initial flavor of the reconstructed  $B$  candidate,  $B_{\text{rec}}$ , using information from the other  $B$  meson,  $B_{\text{tag}}$ , in the event. The decay rate  $g_+$  ( $g_-$ ) for a neutral  $B$  meson decaying to a  $CP$  eigenstate accompanied by a  $B^0$  ( $\bar{B}^0$ ) tag can be expressed as

$$g_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left\{ (1 \mp \Delta w) \pm (1 - 2w) \times \left[ \frac{2\text{Im}\lambda}{1 + |\lambda|^2} \sin(\Delta m_d \Delta t) - \frac{1 - |\lambda|^2}{1 + |\lambda|^2} \cos(\Delta m_d \Delta t) \right] \right\} \quad (1)$$

where  $\Delta t \equiv t_{\text{rec}} - t_{\text{tag}}$  is the difference between the proper decay times of the reconstructed and tag  $B$  mesons,  $\tau_{B^0}$  is the neutral  $B$  lifetime and  $\Delta m_d$  is the mass difference of the  $B$  meson mass eigenstates determined from  $B^0 - \bar{B}^0$  oscillations [7]. We assume that the corresponding decay-width difference  $\Delta\Gamma_d$  is zero. The average mistag probability  $w$  describes the effect of incorrect tags, and  $\Delta w$

is the difference between the mistag probabilities for  $B^0$  and  $\bar{B}^0$ . The sine term in Eq. 1 results from the interference between direct decay and decay after  $B^0 - \bar{B}^0$  oscillation. A non-zero cosine term arises from the interference between decay amplitudes with different weak and strong phases (direct  $CP$  violation) or from  $CP$  violation in  $B^0 - \bar{B}^0$  mixing. In the SM,  $CP$  violation in mixing and direct  $CP$  violation in  $b \rightarrow c\bar{c}s$  decays are both negligible [3]. Under these assumptions,  $\lambda = \eta_f e^{-2i\beta}$ , where  $\eta_f = \pm 1$  is the  $CP$  eigenvalue of the final state  $f$ . Thus, the time-dependent  $CP$ -violating asymmetry is

$$A_{CP}(\Delta t) \equiv \frac{g_+(\Delta t) - g_-(\Delta t)}{g_+(\Delta t) + g_-(\Delta t)} \quad (2)$$

$$= -(1 - 2w)\eta_f \sin 2\beta \sin(\Delta m_d \Delta t).$$

The *BABAR* detector is described in detail elsewhere [8]. We select a sample of neutral  $B$  mesons ( $B_{CP}$ ) decaying to the  $\eta_f = -1$  final states  $J/\psi K_S^0$ ,  $\psi(2S)K_S^0$ ,  $\chi_{c1}K_S^0$  and  $\eta_c K_S^0$ , and to the  $\eta_f = +1$  final state  $J/\psi K_L^0$ . We reconstruct  $K_S^0 \rightarrow \pi^+ \pi^-$ , except in  $J/\psi K_S^0$ , where we also include  $K_S^0 \rightarrow \pi^0 \pi^0$ . The charmonium mesons are reconstructed in the decays  $J/\psi \rightarrow e^+ e^-$ ,  $\mu^+ \mu^-$ ;  $\psi(2S) \rightarrow e^+ e^-$ ,  $\mu^+ \mu^-$ ,  $J/\psi \pi^+ \pi^-$ ;  $\chi_{c1} \rightarrow J/\psi \gamma$  and  $\eta_c \rightarrow K_S^0 K^+ \pi^-$ . We also reconstruct the  $J/\psi K^{*0}(K^{*0} \rightarrow K_S^0 \pi^0)$  final state, which can be  $CP$ -even or  $CP$ -odd due to the presence of even ( $L=0, 2$ ) and odd ( $L=1$ ) orbital angular momentum contributions. Ignoring the angular information in  $J/\psi K^{*0}$  results in a dilution of the measured  $CP$  asymmetry by a factor  $|1 - 2R_{\perp}|$ , where  $R_{\perp}$  is the fraction of the  $L=1$  contribution. In Ref. [9] we have measured  $R_{\perp} = 0.233 \pm 0.010$  (stat)  $\pm 0.005$  (syst), which gives an effective  $\eta_f = 0.504 \pm 0.033$  for  $f = J/\psi K^{*0}$ , after acceptance corrections.

In addition to the  $CP$  modes described above, we use a sample of  $B^0$  mesons ( $B_{\text{flav}}$ ) decaying to the flavor eigenstates  $D^{(*)-} h^+$  ( $h^+ = \pi^+, \rho^+, a_1^+$ ) and  $J/\psi K^{*0}(K^{*0} \rightarrow K^+ \pi^-)$  to calibrate the flavor-tagging performance and  $\Delta t$  resolution. We also perform studies to measure apparent  $CP$  violation arising from  $CP$ -conserving processes using a control sample of  $B^+$  mesons decaying to the final states  $J/\psi K^{(*)+}$ ,  $\psi(2S)K^+$ ,  $\chi_{c1}K^+$ , and  $\eta_c K^+$ . The event selection and candidate reconstruction remain unchanged from those described in Refs. [5, 10, 11], with the exception of modes containing  $\eta_c$  mesons. In Ref. [5] we reconstructed the  $B^0 \rightarrow \eta_c K_S^0$  and  $B^{\pm} \rightarrow \eta_c K^{\pm}$  modes using the  $\eta_c \rightarrow K_S^0 K^+ \pi^-$  decay, with the requirement  $2.91 < m_{K_S^0 K^+ \pi^-} < 3.05 \text{ GeV}/c^2$ . We now exploit the fact that the  $\eta_c$  decays predominantly through a  $K\pi$  res-



onance at around  $1430 \text{ MeV}/c^2$  and a  $K_S^0 K$  resonance close to threshold, and require that either  $m_{K_S^0 \pi^-}$  or  $m_{K^+ \pi^-}$  be in the mass-range  $[1.26, 1.63] \text{ GeV}/c^2$ , or that  $m_{K^+ K_S^0} \in [1.0, 1.4] \text{ GeV}/c^2$ .

We calculate the time interval  $\Delta t$  between the two  $B$  decays from the measured separation  $\Delta z$  between the decay vertices of  $B_{\text{rec}}$  and  $B_{\text{tag}}$  along the collision ( $z$ ) axis [10]. The  $z$  position of the  $B_{\text{rec}}$  vertex is determined from the charged daughter tracks. The  $B_{\text{tag}}$  decay vertex is determined by fitting tracks not belonging to the  $B_{\text{rec}}$  candidate to a common vertex, while employing constraints from the beamspot location and the  $B_{\text{rec}}$  momentum [10]. Events are accepted if the calculated  $\Delta t$  uncertainty is less than  $2.5 \text{ ps}$  and  $|\Delta t|$  is less than  $20 \text{ ps}$ . The fraction of all events satisfying these requirements is 95 %.

The algorithm used to determine the flavor of the  $B_{\text{tag}}$  at its decay to be either  $B^0$  or  $\bar{B}^0$  is described in detail in Ref. [5]. In brief, we define six mutually exclusive tagging categories in order of decreasing tag purity: **Lepton**, **Kaon I**, **Kaon II**, **Kaon-Pion**, **Pion** and **Other**. The figure-of-merit for tagging is the effective tagging efficiency  $Q \equiv \sum_i \varepsilon_i (1 - 2w_i)^2$ , where  $\varepsilon_i$  is the tagging efficiency of tagging category  $i$ . We measure  $Q = (30.5 \pm 0.3) \%$ , consistent with the results in Ref. [5].

We determine the composition of our final sample using the beam-energy substituted mass  $m_{\text{ES}} = \sqrt{(E_{\text{beam}}^*)^2 - (p_B^*)^2}$ , where  $E_{\text{beam}}^*$  and  $p_B^*$  are the beam energy and  $B$  momentum in the  $e^+e^-$  center-of-mass (CM) frame. For the  $J/\psi K_L^0$  mode we instead use the difference  $\Delta E$  between the candidate CM energy and  $E_{\text{beam}}^*$ . The composition of our final sample is shown in Fig. 1. We use events with  $m_{\text{ES}} > 5.2 \text{ GeV}/c^2$  ( $|\Delta E| < 80 \text{ MeV}$  for  $J/\psi K_L^0$ ) to determine the properties of the background contributions. We define a signal region  $5.27 < m_{\text{ES}} < 5.29 \text{ GeV}/c^2$  ( $|\Delta E| < 10 \text{ MeV}$  for  $J/\psi K_L^0$ ), which contains 12677  $CP$  candidate events that satisfy the tagging and vertexing requirements (see Table I). For all modes except  $\eta_c K_S^0$  and  $J/\psi K_L^0$ , we use simulated events to estimate the fractions of events that peak in the  $m_{\text{ES}}$  signal region due to cross-feed from other decay modes (peaking background). For the  $\eta_c K_S^0$  mode, the cross-feed fraction is determined from a fit to the  $m_{KK\pi}$  and  $m_{\text{ES}}$  distributions in data. For the  $J/\psi K_L^0$  decay mode, the sample composition, effective  $\eta_f$ , and  $\Delta E$  distribution of the individual background sources are determined either from simulation (for  $B \rightarrow J/\psi X$ ) or from the  $m_{\ell^+ \ell^-}$  sidebands in data (for non- $J/\psi$  background).

We determine  $\sin 2\beta$  and  $|\lambda|$  from a simultaneous maximum likelihood fit to the  $\Delta t$  distribution of the tagged  $B_{CP}$  and  $B_{\text{flav}}$  samples. The  $\Delta t$  distributions of the  $B_{CP}$  sample are modeled by Eq. 1. Those of the  $B_{\text{flav}}$  sample evolve according to Eq. 1 with  $\lambda = 0$ . The observed amplitudes for the  $CP$  asymmetry in the  $B_{CP}$  sample and for flavor oscillation in the  $B_{\text{flav}}$  sample are reduced by the same factor,  $1 - 2w$ , due to flavor mistags. The  $\Delta t$  distributions for the signal are convolved with a resolution

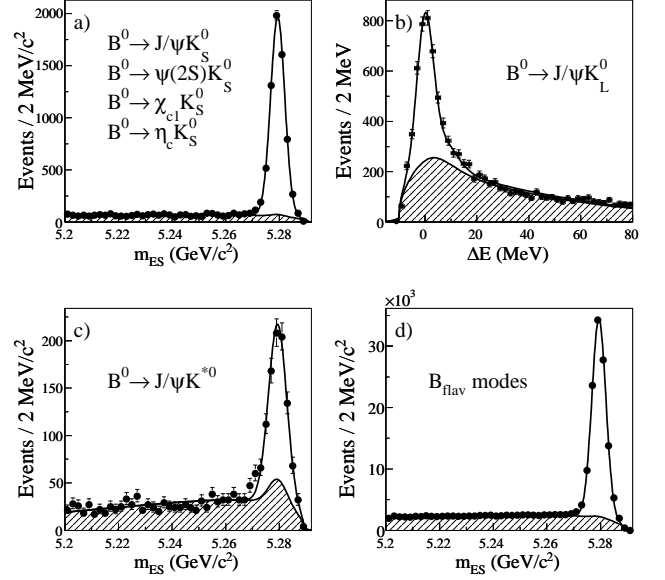


FIG. 1: Distributions for  $B_{CP}$  and  $B_{\text{flav}}$  candidates satisfying the tagging and vertexing requirements: a)  $m_{\text{ES}}$  for the final states  $J/\psi K_S^0$ ,  $\psi(2S) K_S^0$ ,  $\chi_{c1} K_S^0$ , and  $\eta_c K_S^0$ , b)  $\Delta E$  for the final state  $J/\psi K_L^0$ , c)  $m_{\text{ES}}$  for  $J/\psi K^{*0} (K^{*0} \rightarrow K_S^0 \pi^0)$ , and d)  $m_{\text{ES}}$  for the  $B_{\text{flav}}$  sample. In each plot, the shaded region is the estimated background contribution.

function common to both the  $B_{\text{flav}}$  and  $B_{CP}$  samples, modeled by the sum of three Gaussian functions [10]. The combinatorial background is incorporated with an empirical description of its  $\Delta t$  spectra, containing prompt and non-prompt lifetime components convolved with a resolution function [10] distinct from that of the signal. The peaking background is assigned the same  $\Delta t$  distribution as the signal but with no  $CP$  violation, with the same  $\Delta t$  resolution function.

In addition to  $\sin 2\beta$  and  $|\lambda|$ , there are 68 free parameters in the  $CP$  fit. For the signal, these are the parameters of the  $\Delta t$  resolution (7), the average mistag fractions  $w$  and the differences  $\Delta w$  between  $B^0$  and  $\bar{B}^0$  mistag fractions for each tagging category (12), and the difference between  $B^0$  and  $\bar{B}^0$  reconstruction and tagging efficiencies (7). The background is described by mistag fractions (24), parameters of the  $\Delta t$  resolution (3) and  $B_{\text{flav}}$  time dependence (3), and parameters for the  $CP$  background (8), including the apparent  $CP$  asymmetry of non-peaking events in each tagging category. Finally, we allow for the possibility of direct  $CP$  violation in the  $\chi_{c1} K_S^0$  background to  $J/\psi K^{*0}$  (1), and in the main backgrounds to the  $J/\psi K_L^0$  mode, coming from  $J/\psi K_S^0$ ,  $J/\psi K^{*0}$ , and the remaining  $J/\psi$  background (3 parameters). The effective  $|\lambda|$  of the non- $J/\psi$  background is fixed from a fit to the  $J/\psi$ -candidate sidebands in  $J/\psi K_L^0$ . We fix  $\tau_{B^0} = 1.530 \text{ ps}$  and  $\Delta m_d = 0.507 \text{ ps}^{-1}$  [7]. The determination of the mistag fractions and  $\Delta t$  resolution function parameters for the signal is dominated by the  $B_{\text{flav}}$  sample, about 10 times more abundant than the

TABLE I: Number of events  $N_{\text{tag}}$  and signal purity  $P$  in the signal region after tagging and vertexing requirements, and results of fitting for  $CP$  asymmetries in the  $B_{CP}$  sample and various subsamples. In addition, fit results for the  $B_{\text{flav}}$  and  $B^+$  control samples demonstrate that no artificial  $CP$  asymmetry is found where we expect no  $CP$  violation ( $\sin 2\beta = 0$ ,  $|\lambda| = 1$ ). Errors are statistical only.

Sample	$N_{\text{tag}}$	$P(\%)$	$\sin 2\beta$	$ \lambda $
Full $CP$ sample	12677	75	$0.714 \pm 0.032$	$0.952 \pm 0.022$
$J/\psi K_S^0 (\pi^+ \pi^-)$	4459	96	$0.702 \pm 0.042$	$0.976 \pm 0.030$
$J/\psi K_S^0 (\pi^0 \pi^0)$	1086	88	$0.617 \pm 0.103$	$0.812 \pm 0.058$
$\psi(2S) K_S^0$	687	83	$0.947 \pm 0.112$	$0.867 \pm 0.079$
$\chi_{c1} K_S^0$	313	89	$0.759 \pm 0.170$	$0.804 \pm 0.102$
$\eta_c K_S^0$	328	69	$0.778 \pm 0.195$	$0.948 \pm 0.141$
$J/\psi K_L^0$	4748	55	$0.734 \pm 0.074$	$1.061 \pm 0.063$
$J/\psi K^{*0}$	1056	66	$0.477 \pm 0.271$	$0.954 \pm 0.083$
$J/\psi K^0$	10275	76	$0.697 \pm 0.035$	$0.966 \pm 0.025$
$J/\psi K_S^0$	5547	94	$0.686 \pm 0.039$	$0.950 \pm 0.027$
$\eta_f = -1$	6873	92	$0.711 \pm 0.036$	$0.935 \pm 0.024$
1999-2002 data	3084	79	$0.735 \pm 0.063$	$0.987 \pm 0.045$
2003-2004 data	4850	77	$0.728 \pm 0.052$	$0.940 \pm 0.035$
2005-2006 data	4725	74	$0.681 \pm 0.054$	$0.940 \pm 0.037$
Lepton	1349	80	$0.728 \pm 0.066$	$0.901 \pm 0.043$
Kaon I	1843	76	$0.689 \pm 0.063$	$0.986 \pm 0.046$
Kaon II	2948	72	$0.751 \pm 0.071$	$0.880 \pm 0.044$
Kaon-Pion	2321	73	$0.654 \pm 0.112$	$0.999 \pm 0.075$
Pion	2551	76	$0.671 \pm 0.167$	$0.927 \pm 0.104$
Other	1665	73	$0.705 \pm 0.504$	$1.506 \pm 0.483$
$B_{\text{flav}}$ sample	123893	85	$0.018 \pm 0.010$	$0.995 \pm 0.007$
$B^+$ sample	29598	94	$0.012 \pm 0.017$	$1.010 \pm 0.012$

$CP$  sample.

The fit to the  $B_{CP}$  and  $B_{\text{flav}}$  samples yields  $\sin 2\beta = 0.714 \pm 0.032$  and  $|\lambda| = 0.952 \pm 0.022$ , where the errors are statistical only. The correlation between these two parameters is  $-1.5\%$ . We also perform a separate fit in which we allow different  $\sin 2\beta$  and  $|\lambda|$  values for each charmonium decay mode, a fit to the  $J/\psi K_S^0 (\pi^+ \pi^- + \pi^0 \pi^0)$  mode, and a fit to the  $J/\psi K^0 (K_S^0 + K_L^0)$  sample. We split the data sample by run period and by tagging category. We perform the  $CP$  measurements on control samples with no expected  $CP$  asymmetry. The results of these fits are summarized in Table I. The difference in the  $\eta_c K_S^0 \sin 2\beta$  value with respect to our previous publication [5] is partly due to the slightly different reconstruction algorithms and partly to the different selection; the two measurements are consistent when the systematic error is taken into account.

Figure 2 shows the  $\Delta t$  distributions and asymmetries in yields between events with  $B^0$  tags and  $\bar{B}^0$  tags for the  $\eta_f = -1$  and  $\eta_f = +1$  samples as a function of  $\Delta t$ , overlaid with the projection of the likelihood fit result. We also performed the  $CP$  fit fixing  $|\lambda| = 1$ , which yields  $\sin 2\beta = 0.713 \pm 0.032$  (stat).

The dominant systematic errors on  $\sin 2\beta$  are due to limited knowledge of various background properties, including uncertainties in  $J/\psi K_L^0$ -specific backgrounds and in

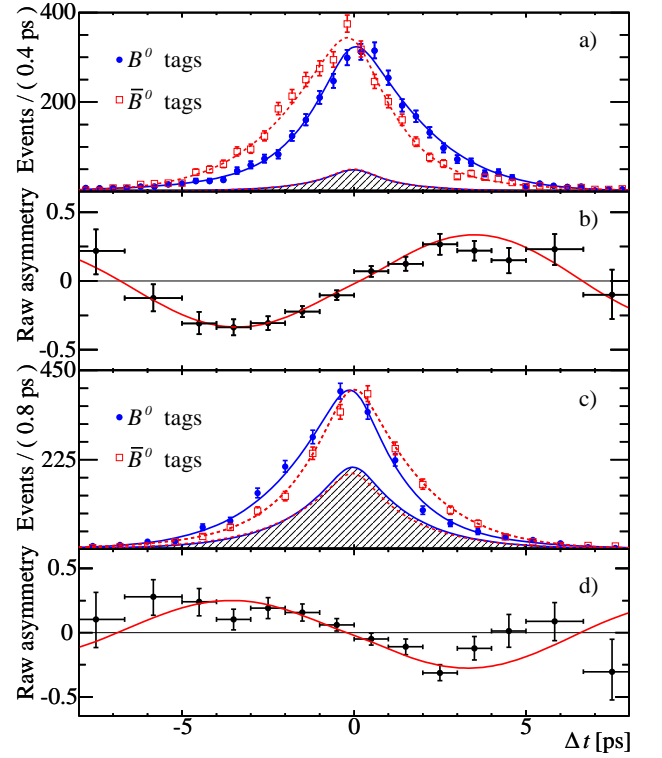


FIG. 2: a) Number of  $\eta_f = -1$  candidates ( $J/\psi K_S^0$ ,  $\psi(2S) K_S^0$ ,  $\chi_{c1} K_S^0$ , and  $\eta_c K_S^0$ ) in the signal region with a  $B^0$  tag ( $N_{B^0}$ ) and with a  $\bar{B}^0$  tag ( $N_{\bar{B}^0}$ ), and b) the raw asymmetry,  $(N_{B^0} - N_{\bar{B}^0}) / (N_{B^0} + N_{\bar{B}^0})$ , as functions of  $\Delta t$ . Figures c) and d) are the corresponding distributions for the  $\eta_f = +1$  mode  $J/\psi K_L^0$ . To enhance the signal component, all distributions exclude **Other**-tagged events. The solid (dashed) curves represent the fit projections in  $\Delta t$  for  $B^0$  ( $\bar{B}^0$ ) tags. The shaded regions represent the estimated background contributions.

the amounts of peaking backgrounds and their  $CP$  asymmetries (0.010), to possible differences between the  $B_{\text{flav}}$  and  $B_{CP}$  tagging performances (0.009), to the description of the  $\Delta t$  resolution functions (0.008), to the knowledge of the event-by-event beamspot position (0.005). The only sizeable systematic uncertainties on  $|\lambda|$  are due to the possible interference between the suppressed  $\bar{b} \rightarrow \bar{u} c \bar{d}$  amplitude with the favored  $b \rightarrow c \bar{u} d$  amplitude for some tag-side  $B$  decays [12] (0.015), and to the  $CP$  content of the peaking backgrounds (0.006). The total systematic error on  $\sin 2\beta$  ( $|\lambda|$ ) is 0.018 (0.017). The main systematic uncertainties on both  $\sin 2\beta$  and  $|\lambda|$  for the full sample, for the seven individual modes, and for the fits to the  $J/\psi K^0$  and  $J/\psi K_S^0$  samples are summarized in the Table at [13].

The large  $B_{CP}$  sample allows a number of consistency checks, including separation of the data by decay mode and tagging category. The results of those checks, all consistent within the errors, are listed in Table I. We observe no statistically significant asymmetry from fits to the control samples of non- $CP$  decay modes.

In summary, we report improved measurements of  $\sin 2\beta$  and  $|\lambda|$  that supersede our previous results [5]. We

measure  $\sin 2\beta = 0.714 \pm 0.032$  (stat)  $\pm 0.018$  (syst) and  $|\lambda| = 0.952 \pm 0.022$  (stat)  $\pm 0.017$  (syst), providing an improved model-independent constraint on the position of the apex of the unitarity triangle [14]. Our measurements agree within errors with the published results [15, 16] and with the theoretical estimates of the magnitudes of CKM matrix elements in the context of the SM [17]. The measured value of  $|\lambda|$  is consistent with no direct  $CP$  violation with a significance of 1.72 standard deviations. We report the first individual measurements of  $\sin 2\beta$  and  $|\lambda|$  for each of the decay modes within our  $CP$  sample, and of the  $J/\psi K^0(K_S^0 + K_L^0)$  sample.

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